HELMHOLTZ

RESEARCH FOR
GRAND CHALLENGES

PROBING DENSE MATTER WITH THE DIELECTRON PROBE AT HADES

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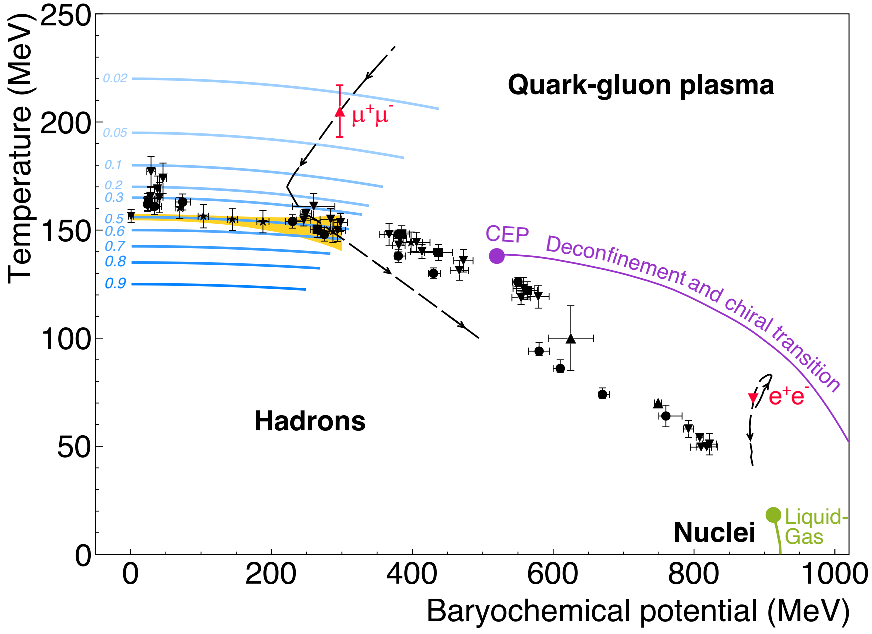
IJClab Dilepton Workshop | 25 Nov 2021

HADES GSI FAIR Phase 0 Research Program TECHNISCHE UNIVERSITÄT DARMSTADT

THE HADES PHYSICS CASE



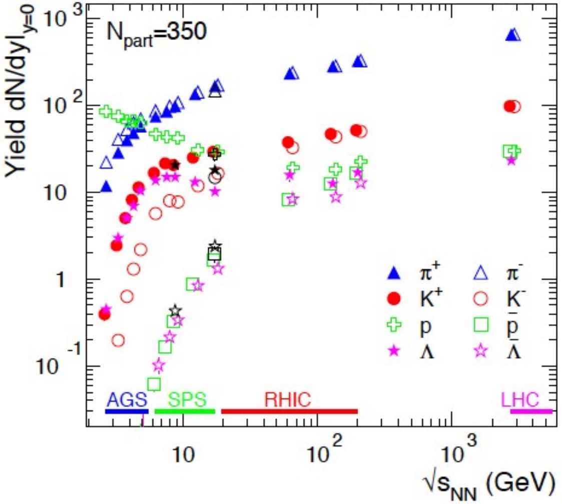
- Explore high-μ_B region of the QCD phase diagram
- Focus on rare and penetrating probes
- Address various aspects of baryon-meson coupling

- **π and p beams:**
  - Reference measurement (vacuum, cold nuclear matter)
  - em structure of baryons/hyperons in time-like region
- **Heavy-ion collisions $\sqrt{s_{NN}} = 2 - 2.4\ GeV$:**
  - Microscopic properties of baryon dominated matter
  - Equation-of-State:
    - E-b-e correlations and fluctuations
    - Flavour production and collective effects
    - Dileptons

HADES Collab., Nature Phys. 15 (2019) 10, 1040-1045
Andronic *et al.*, Nature 561 (2018) no.7723
LQCD: Borsanyi *et al.* [Wuppertal-Budapest Collab.], JHEP 1009 (2010) 073
LQCD: Bazavov *et al.*, Phys.Lett.B 795 (2019) 15-21

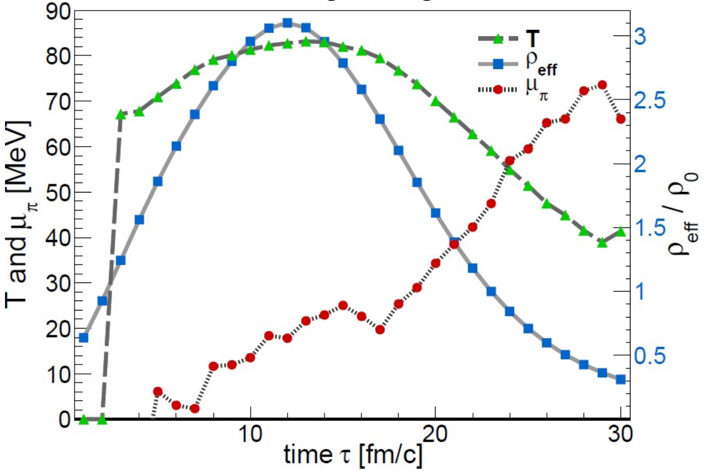
BARYONIC MATTER AT FEW GeV BEAM ENERGY

Hadron yields at freeze out



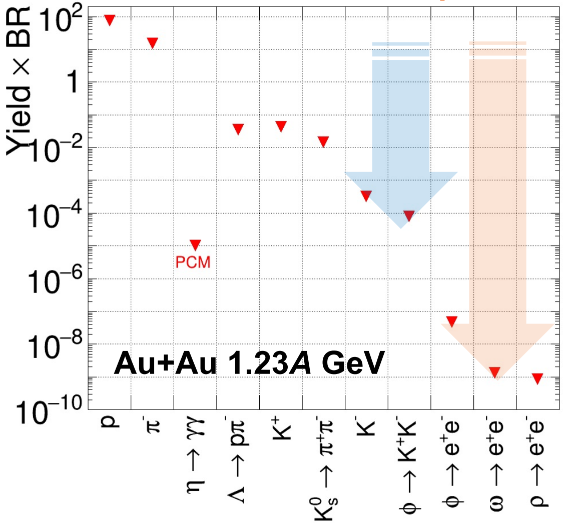
Andronic, Int.J.Mod.Phys.A 29 (2014) 1430047

Thermodynamic properties from coarse graining UrQMD



TG, Seck, Rapp, Stroth, EPJA 52 (2016) 131

Rare probes!



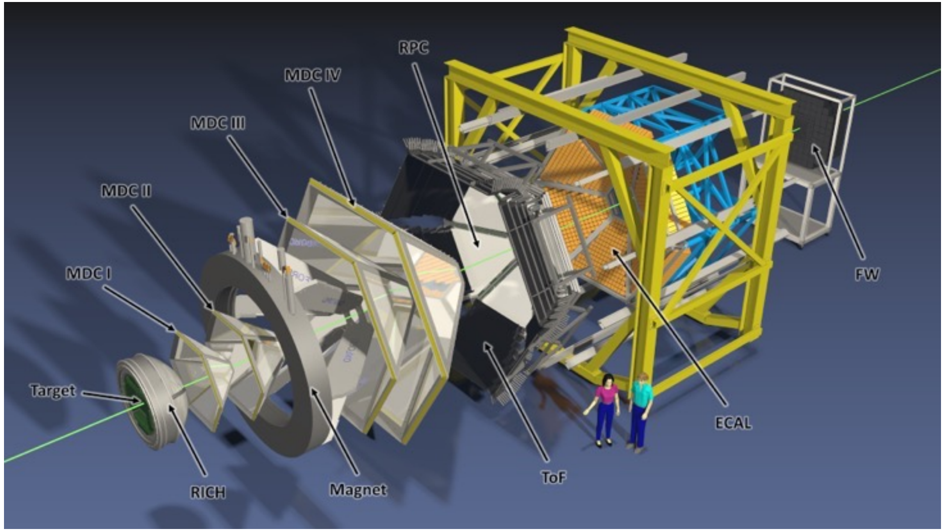
Nucleons stopped in collision zone:
⇝ baryon-dominated system
$(N_B \cong 10 N_\pi)$

~13 fm lifetime of interacting fireball:
T < 70 MeV, $\rho < 3\rho_0$

Strangeness and vector-mesons production below free *NN* threshold

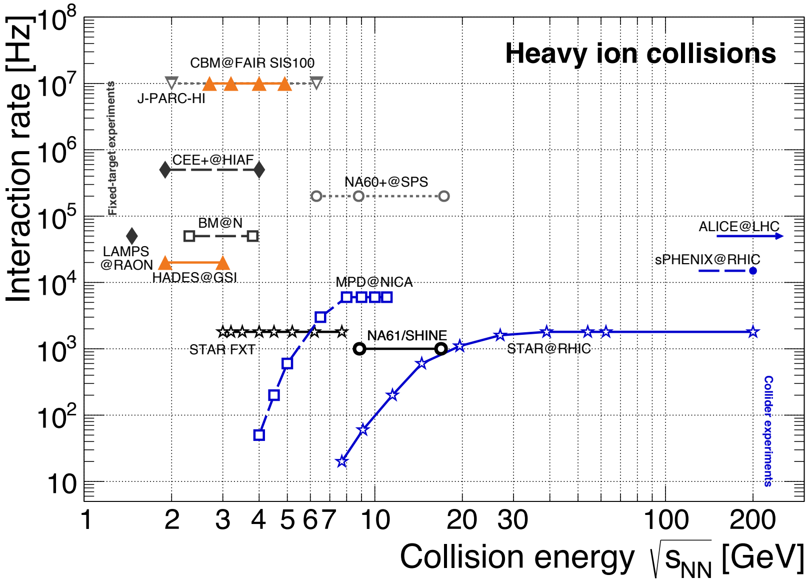
Dilepton production suppressed by the factor α^2

SOME BASIC FACTS ON HADES



- (low-mass) Fixed-target setup
- Large acceptance ⇝ full azimuth, polar from 18° to 85°
- Mass resolution ⇝ few % in the vector-meson region
- Efficient track reconstruction and particle identification
- Fast detector ⇝ accepted trigger rates:
  15 kHz for heavy-ions, 50 kHz for hadron beams

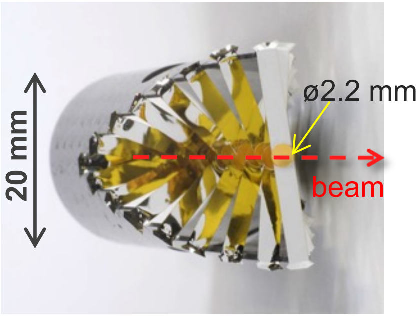
TG, Nucl.Phys. A982 (2019), update 2021
CBM Collab., EPJA 53 3 (2017) 60

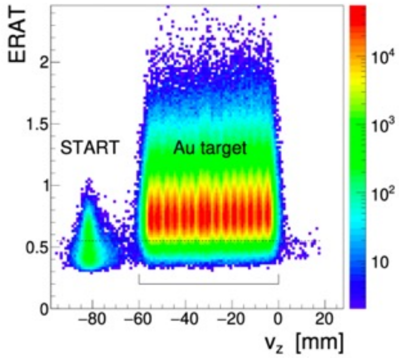


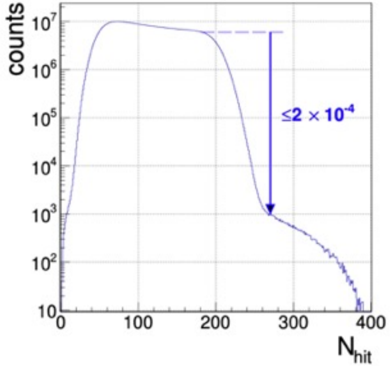
EVENT RECONSTRUCTION

15-fold segmented Au/Ag target

- Δz = 3.7 mm; 25 μm disc x 15
- 1.5-2% interaction probability
- target region free of magnetic field

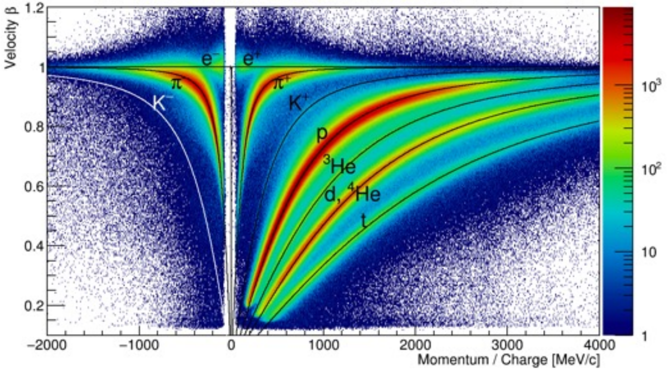






- 7×10^9 events recorded
  - trigger on 43% most central collisions
  - min. bias events scaled down (f=8)
- Event pile-up $\leq 2.5\times10^{-4}$

Particle identification by means of:
velocity, momentum, dE/dx, RICH information ⇝ all combined in a multivariate analysis (neural network)



Centrality estimator:
off-line centrality selection based on hit or track multiplicity and/or Forward Wall integral charge

HADES Collab., Eur.Phys.J.A 54 (2018) 5, 85

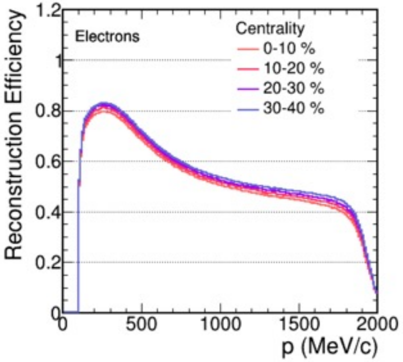
Event plane reconstruction:
based on hits of charged projectile spectators in the FW

HADES, Phys.Rev.Lett. 125 (2020) 262301

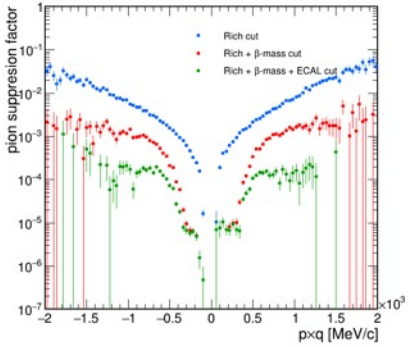
ELECTRON IDENTIFICATION

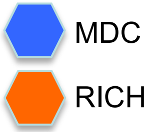
- Reconstruction efficiency 50 – 80%
  ⇝ embedding of simulated tracks to real events
- Pion suppression factor $10^{-5} - 10^{-4}$
  ⇝ full Monte Carlo simulations

Electron efficiency

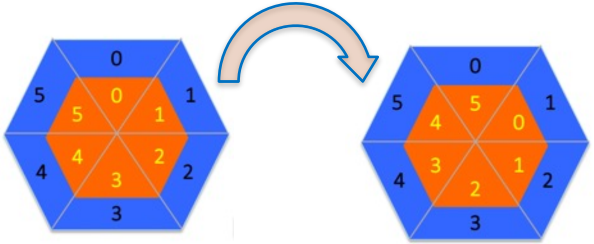


Pion suppression factor





Data driven purity estimates using rich rotation technique

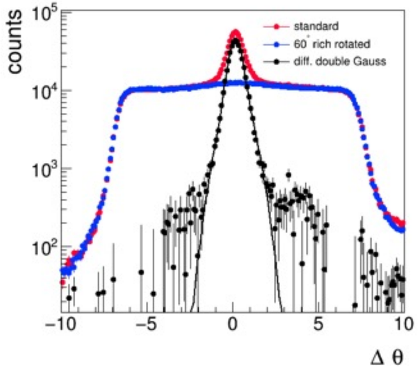


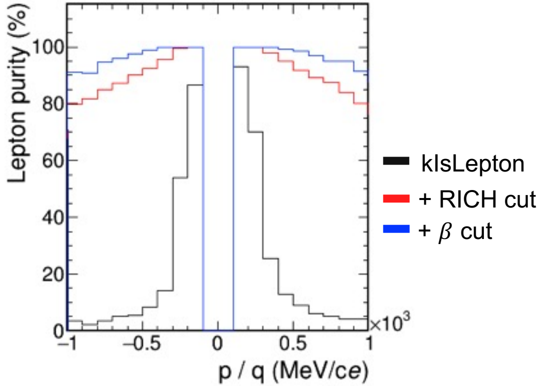
Rotate RICH software-wise in steps of 60^{O}

Correlate tracks with rings

Get random matches

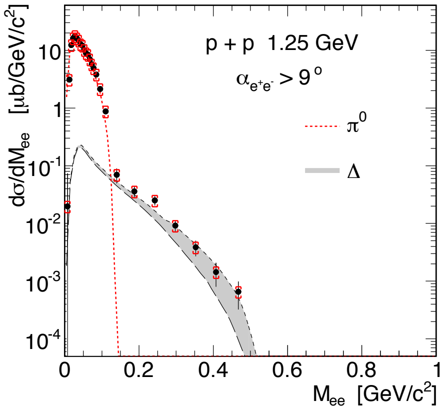
$$Purity = \frac{S}{S+BG} = \frac{all\ - rich\, rot.}{all}$$

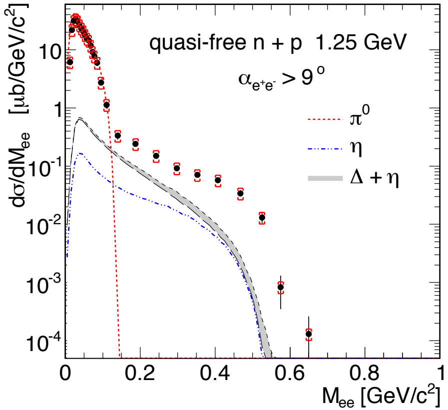




REFERENCE MEASUREMENTS

LEPTON PAIRS FROM pp AND np REACTIONS AT 1.25 GeV



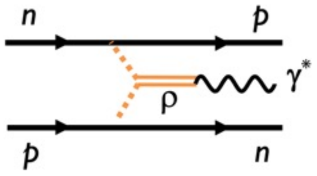


Goals:

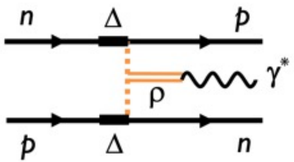
- reference measurement for Au+Au at 1.23*A* GeV
- exploring hadron electromagnetic structure

Results:

- remarkable isospin effect
- radiation from the internal line yields enhanced emission at high invariant masses ⇝ off-shell (cloud-cloud) $\pi\pi$ collision



Shyam and Mosel,
PRC 82 (2010) 062201

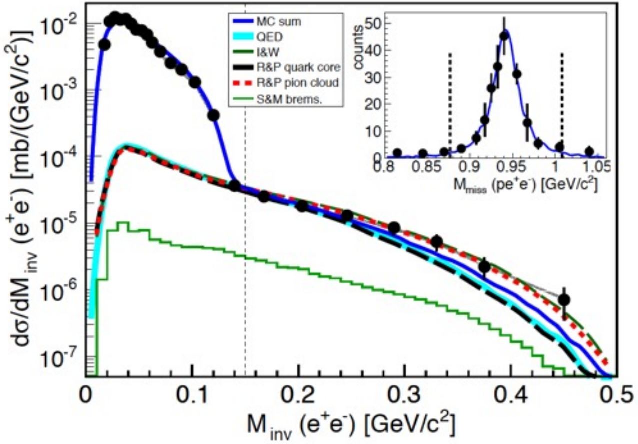


Bashkanov and Clement,
Eur. Phys. J. A50 (2014)

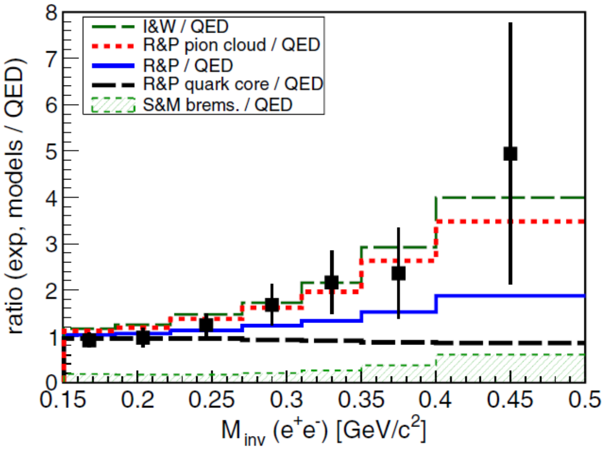
HADES Collab., PLB 690 (2010) 118, Eur.Phys.J. A53 (2017) 149

EXCLUSIVE ANALYSIS OF $pp \rightarrow ppe^+e^-$

Pion cloud effect in $\Delta(1232)$



- First direct access to the $\Delta(1232)$ electromagnetic transition form factor in the time-like region
  - deviation from "point-like" transition
  - effect of the pion cloud observed (off-shell ρ meson)



Krivoruchenko et al. Phys. Rev. D65(2002) 017502 - QED: point like $\gamma^* NR$
Iachello and Wan, PRC 69, 055204 (2004) - two component quark model
Peña and Ramalho, PRD 93, 033004 (2016) - covariant constituent quark model
Shyam and Mosel, PRC 82, 062201 (2010)

First measurement: PDG 2018

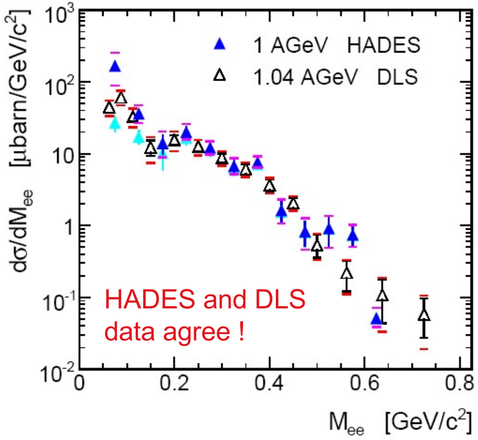
Δ(1232) BRANCHING RATIOS

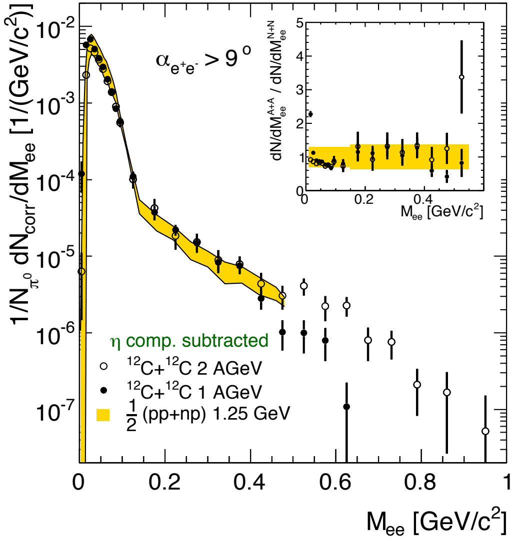
$\Gamma(pe^+e^-)/\Gamma_{total}$

VALUE (units 10^{-5})	*DOCUMENT ID*
4.19±0.34±0.62	[1] ADAMCZEW... 17

[1] The systematic uncertainty includes the model dependence.

HADES Collab., PRC 95, 065205 (2017)





DILEPTONS FROM C+C AT 1 AND 2*A* GeV

- Enhanced pair yield above η-contribution established
  - „True" excess from dense phase?
  - Contribution from the initial phase?

- C+C data reproduced (within 20%) by superposition of NN interactions
- Pair "excess" observed in C+C data has been traced back to anomalous pair production in np collisions
- No true medium effects observed, at least not for C+C data

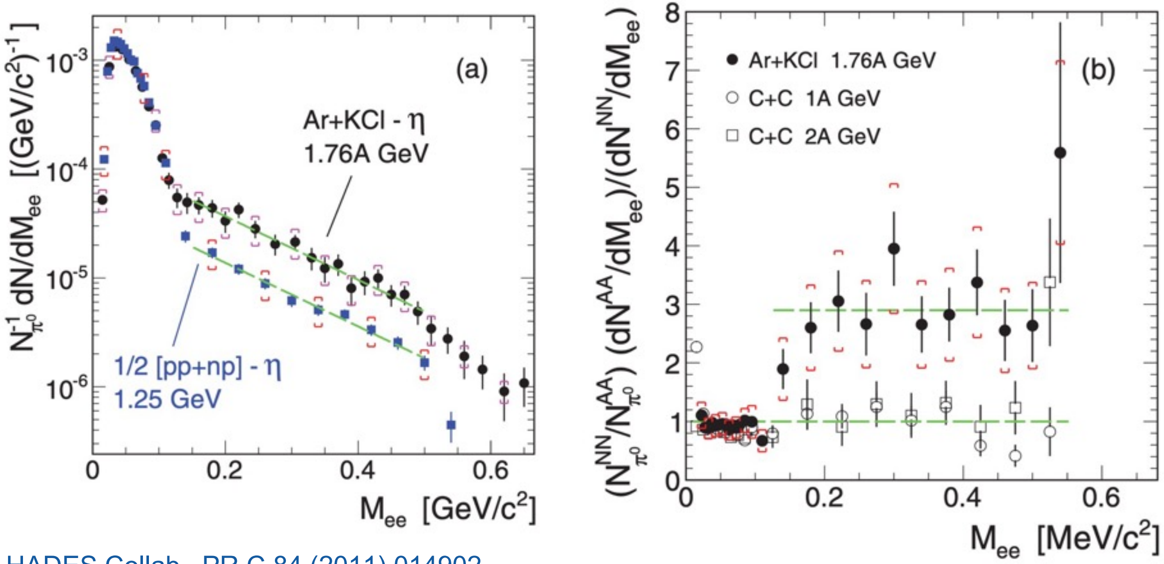
How does the excess evolves with system size?

HADES Collab., PRL 98(2007) 052302
HADES Collab., PLB 663 (2008) 43
HADES Collab., PLB 690 (2010) 118

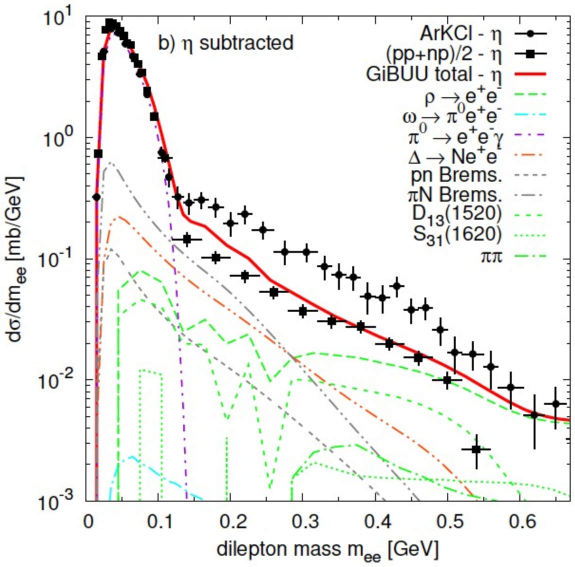
THERMAL RADIATION

DILEPTONS FROM 1.76*A* GeV Ar+KCl COLLISIONS

- Isolation of excess by a comparison with **measured**
  - “reference” spectrum – the NN reference
  - decays of mesons (π^0, η, ω, ϕ) at freeze-out
- First evidence for radiation from the “medium” in this energy regime
- Models with vacuum SF misses data ⇝ room for medium modifications



HADES Collab., PR.C 84 (2011) 014902

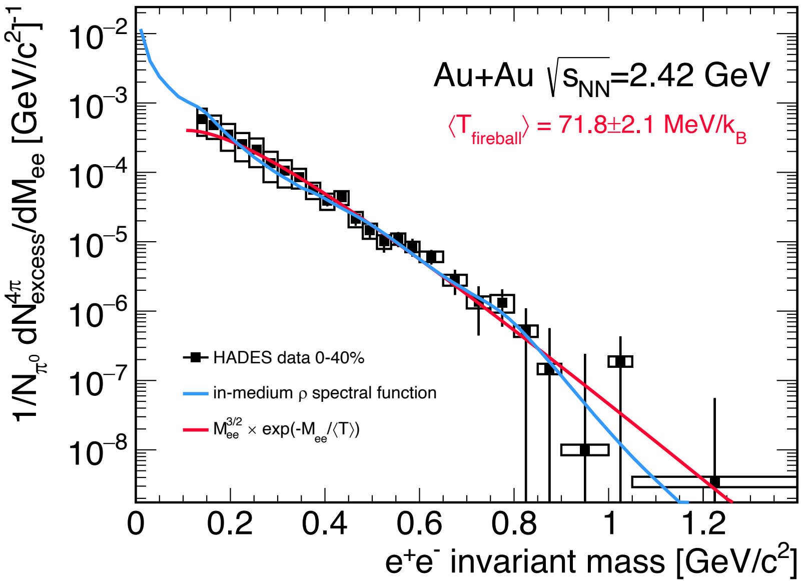


Weil, J.Phys.Conf.Ser. 426 (2013) 012035
sf. Endres, J.Phys.Conf.Ser. 503 (2014) 012039

THERMAL DILEPTONS FROM 1.23*A* GeV Au+Au COLLISIONS

dilepton invariant mass ⇝ unique direct access to in-medium spectral function

[HADES] Nature Phys. 15(2019) 1040



CG GSI-Texas A&M: Eur. Phys. J. A, 52 5 (2016) 131
CG FRA: Phys. Rev. C 92, 014911 (2015)
CG SMASH: Phys.Rev.C 98 (2018) 5, 054908

$$\frac{dN_{ll}}{d^4x d^4q} = -\frac{\alpha_{em}^2}{\pi^3 M^2} L(M^2) f^B(q\cdot u; T)\, Im\Pi_{em}(M, q; \mu_B, T)$$

McLerran - Toimela formula, Phys. Rev. D 31 (1985) 545

HADES data

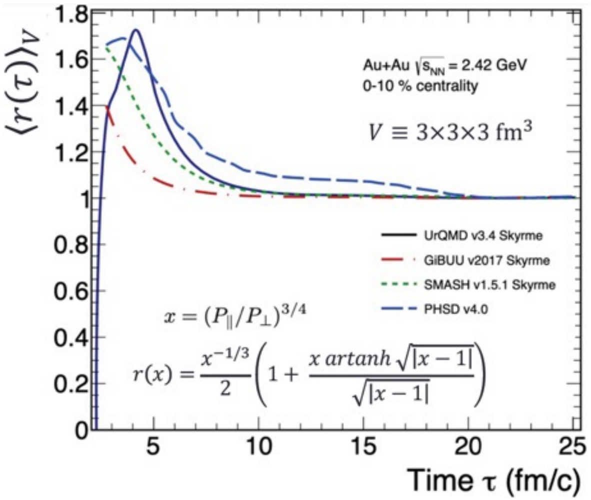
- Thermal rates folded with coarse-grained medium evolution from transport works at low energies
- **melting of ρ! coupling to baryons are important**
- spectrum falls exponentially $\frac{dR_{ll}}{dM} \propto (MT)^{\frac{3}{2}} \exp(-\frac{M}{T})$
- thermometer: independent of flow, no blue shift!

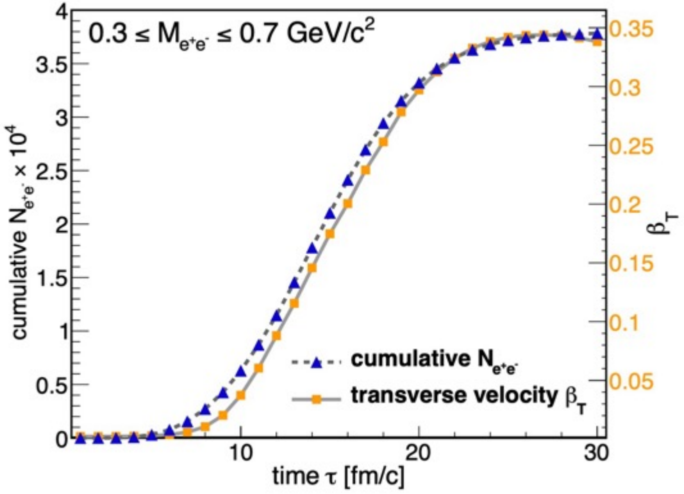
THE "QUEST" FOR THERMALIZATION AT SIS18

Coarse-grained transport approach

- ☐ simulate events with a transport model ⇝ ensemble average to obtain smooth space-time distributions
- ☐ divide space-time in 4-dimensional cells, determine for each cell the bulk properties like T, ρ_B, μ_π, collective velocity
- ☐ use in-medium ρ & ω spectral functions to compute EM emission rates

Huovinen et al., PRC 66 (2002) 014903
CG FRA Endres et al.: PRC 92 (2015) 014911
CG GSI-Texas A&M TG et al.: EPJA 52 (2016) no.5, 131
CG SMASH: Phys.Rev.C 98 (2018) 5, 054908

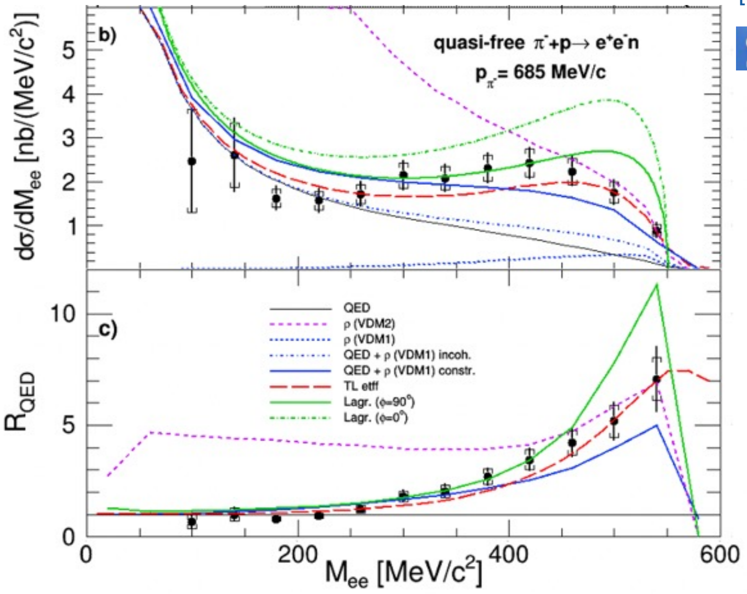




MESON CLOUD

exclusive analysis $\pi^- p \rightarrow e^+ e^- n$

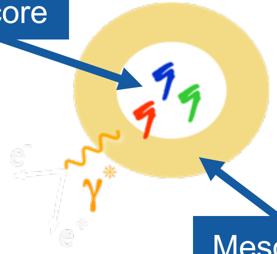
HADES, in preparation



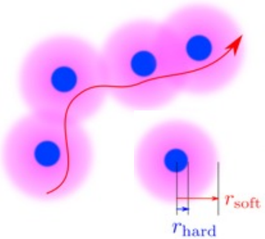
Ramalho, Pena, Phys. Rev. D95 (2017) 014003
Zetenyi, Nitt, Buballa, Galatyuk, Phys. Rev. C arXiv:2012.07546
Speranza *et al.*, Phys.Lett. B764 (2017) 282

[HADES] Phys.Rev.C 102 (2020) 2, 024001
[HADES] Phys.Rev.C 95 (2017) 065205

4 first entries ($N\rho$)
4 additional entries
first entry BR $\Delta \rightarrow pe^+e^-$



- study the structure of the nucleon as an extended object (quark core and meson cloud)
- dominance of the $N^*(1520)$ resonance
  - ontribution fixed by analysis of $\pi^+\pi^-$ channel with PWA



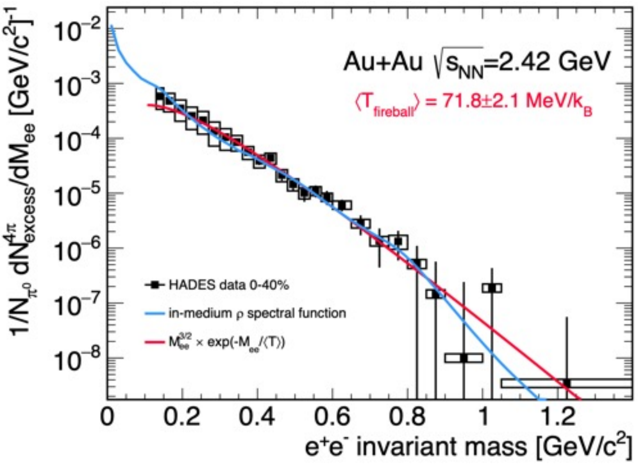
connection to "soft deconfinement"?

Fukushima, Kojo, Weise, PRD 102 (2020) 9, 096017

quantum percolation of the interaction meson clouds

WHAT HAVE WE LEARNT FROM EXCESS RADIATION Au+Au $\sqrt{s_{NN}}$=2.4 GeV?

invariant mass

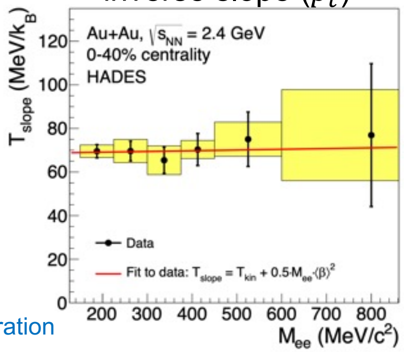


[HADES] Nature Phys. 15(2019) 1040

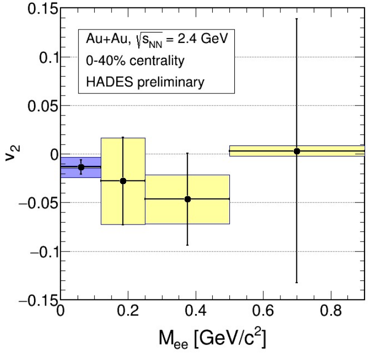
Radiation from a source

- long-lived ($\tau \approx 13\ fm$)
- in local thermal equilibrium
- $\langle T \rangle \approx 72$ MeV
- $\rho = 2 - 3\ \rho_0$

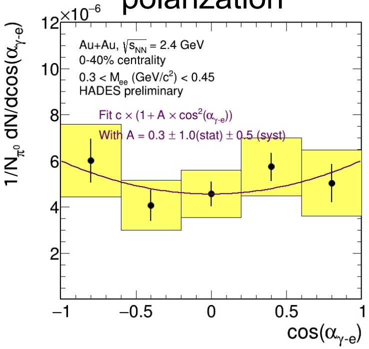
inverse slope (p_t)



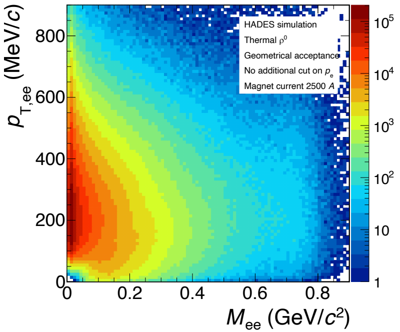
elliptic flow (v_2)



polarization



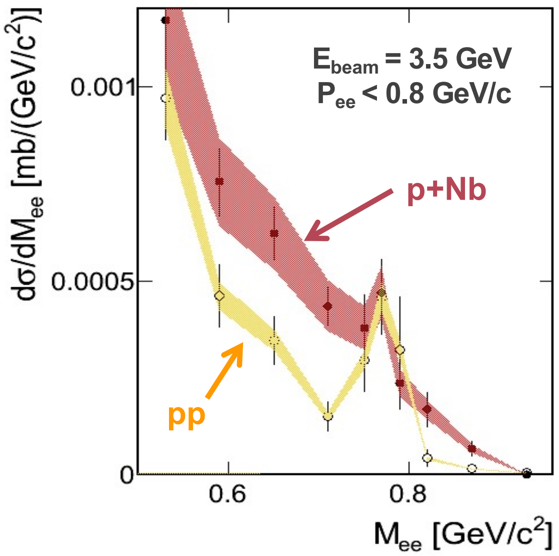
electrical conductivity?



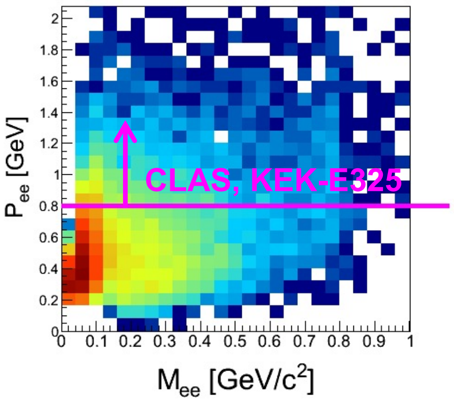
[HADES] in preparation

COLD MATTER

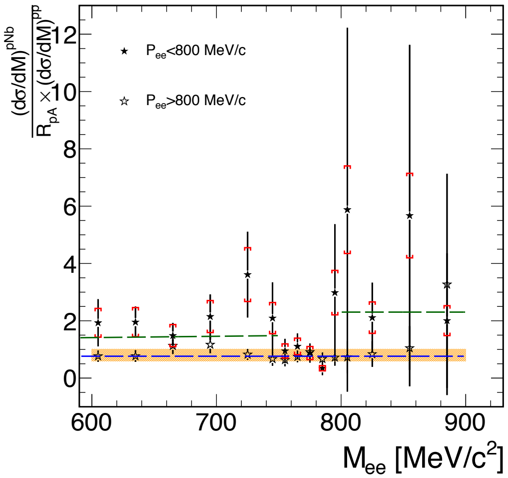
VECTOR MESONS IN COLD MATTER



- Ideal probe to monitor possible line-shape modifications
- Low relative momentum to medium needed to increase sensitivity



HADES Collab., Phys.Lett. B715 (2012)

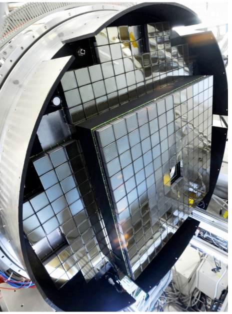


- First measurement of in-medium vector meson decays in the relevant momentum region (P_{ee} down to 0.2 GeV/c)
  ⤳ not measured in this region by CLAS, KEK-E325
- HADES sees rather a melting than a shift
- high-momentum ω mesons “decouple” from the medium
- **future measurements in pp and p+Ag at 4.5 GeV with HADES**

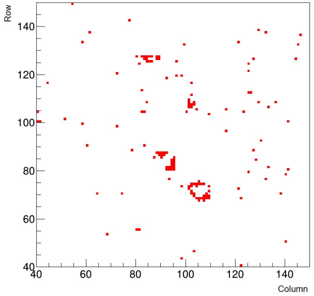
NOW and THEN

MARCH 2019 Ag+Ag COLLISIONS AT $\sqrt{s_{NN}} = 2.42, 2.55$ GeV

new RICH photo detector (with CBM) and ECAL

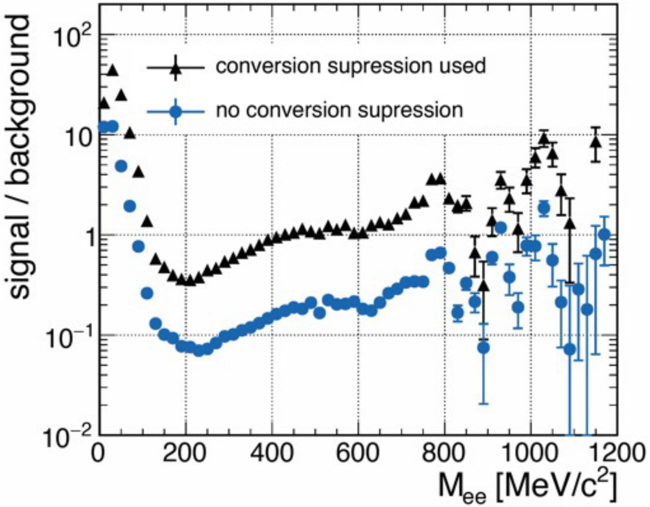


PMT-based RICH photodetector



Event display

- Higher ring detection efficiency
  - factor of 3 better electron identification efficiency
- Suppression of the combinatorial backgound via ring properties
  - factor of 8 better signal-to-background ratio



Number of raw signal pairs

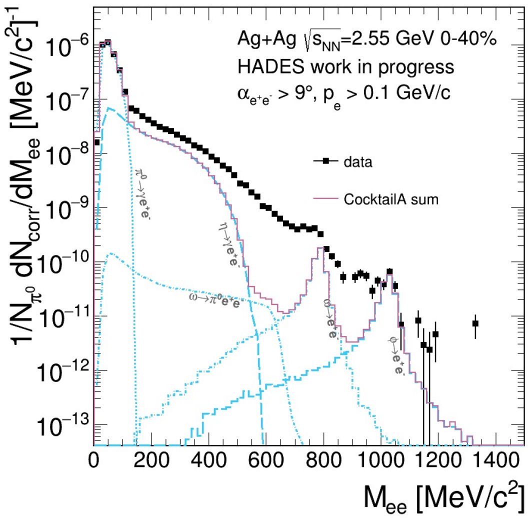
Experiment	# analyzed events	M_{ee} < 0.12 GeV/c^2	0.12 < M_{ee} < 0.45 GeV/c^2	M_{ee} > 0.45 GeV/c^2
Au+Au $(s_{NN})^{1/2}$ = **2.42** GeV	2.4 x 10^9	1.15×10^5	1.53×10^4	581
Ag+Ag $(s_{NN})^{1/2}$ = **2.42** GeV	5.9 x 10^8	1.12×10^5	1.59×10^4	901
Ag+Ag $(s_{NN})^{1/2}$ = **2.55** GeV	4.0 x 10^9	8.80×10^5	1.53×10^5	10916

Very high quality of the data

Ag+Ag work in progress results

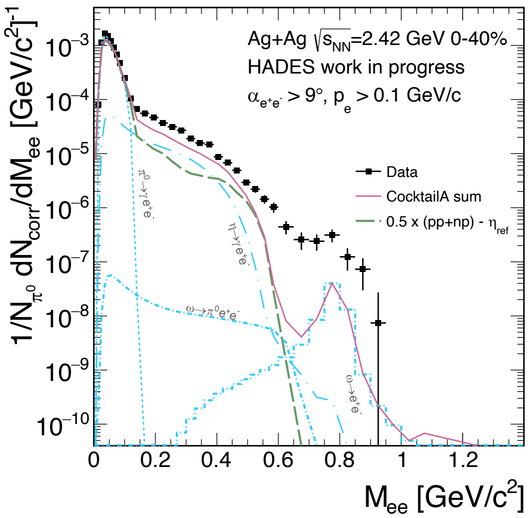
Ag+Ag $\sqrt{s_{NN}} = 2.55$ GeV

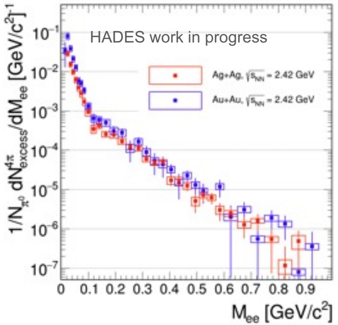
- First measurement of dilepton yield beyond vector meson mass region
- Vector-meson peaks (ω, φ) clearly visible

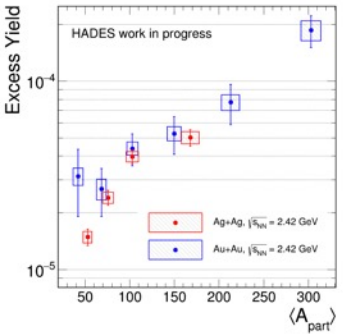


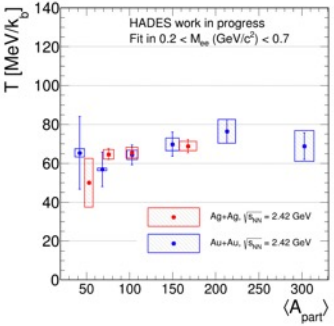
Ag+Ag $\sqrt{s_{NN}} = 2.42$ GeV

- Allows to establish energy, system-size, centrality dependence of the thermal di-electrons









THE UPGRADED HADES DETECTOR (FIVE NEW DETECTOR SYSTEMS)

- ☐ improved physics performance through instrumentation of the very forward hemisphere using FAIR technology
- ☐ in particular important for the Hyperon Program

Forward RPC

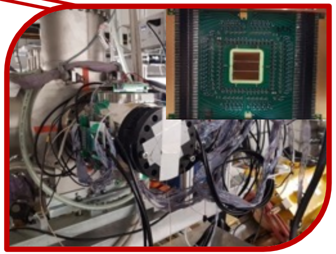
LIP Coimbra

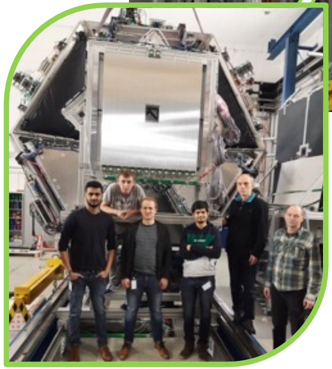
- Based on R&D for neuLAND
- TRB3 read-out

iTOF

TransFAIR, Jülich

- APD read-out
- Enhances trigger purity





STS2

Jagiellonian Univ.

- PANDA straw technology
- PANDA PASTTREC FEE chip

STS1

TransFAIR, Jülich

- PANDA straw technology
- PANDA PASTTREC FEE chip

T0

GSI, TU Darmstadt

- LGAD technology
- In-beam detector

HADES FAIR Phase 0 (5 PROPOSALS SUBMITTED TO G-PAC)

Feb – Mar 2022

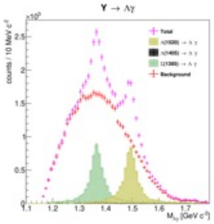

Production and Decay of Hyperons, and Inclusive Hadron and Dilepton Production

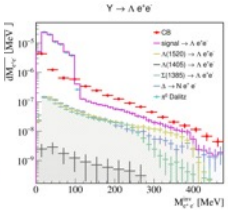
The HADES and HADES-PANDA Collaborations

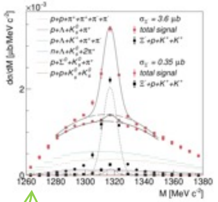
HADES

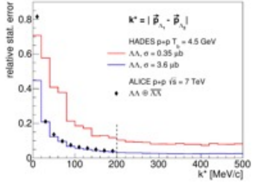
pp 4.5 GeV

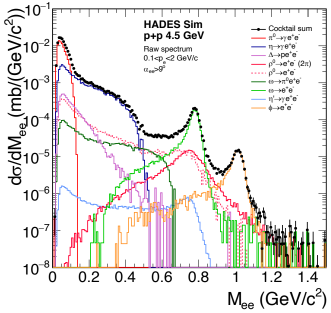
- ☐ Hyperon radiative decays
- ☐ Hyperon Dalitz-decays
- ☐ Doubly strange baryons
- ☐ Double Λ correlation
- ☐ Inclusive e^+e^-











Simulation is assuming
4 weeks of beam with
LH_2 target at 7.5 x 10^7 p/s (ft)
[HADES] Eur. Phys. J. A 57 (2021)

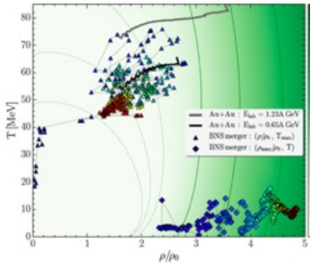
Au+Au BES
0.2-0.8*A* GeV
2022, 2023 ?

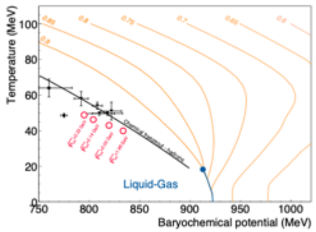

Searching for critical behavior and limitations of the universal freeze-out line

The HADES Collaboration

HADES

- ☐ Laboratory studies of the matter properties (EoS) in compact stellar objects (neutron star mergers)





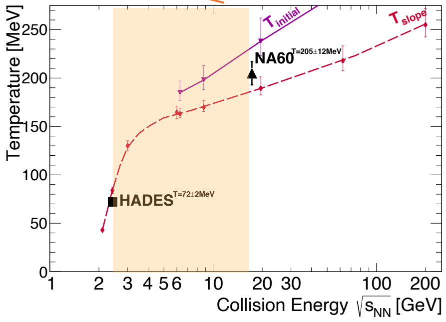
- ☐ What are the measurable consequences of phase transition and critical point in the QCD phase diagram?

RÉSUMÉ AND PROSPECTS

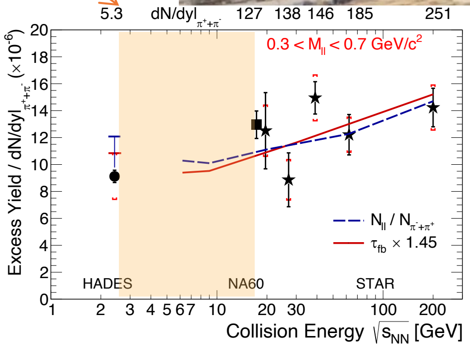
Encouraging prospects for studying baryon dominated QCD matter with HADES

- ☐ HADES provides high-quality data of the dielectron production
- ☐ Unique possibility of characterizing properties of baryon rich QCD matter
- ☐ Complementary program on exclusive measurements in π, p induced reactions
- ☐ Strong scientific program for FAIR Phase-0
- ☐ … and for FAIR Phase-1 with HADES and CBM

[movie FAIR status Apr 2020]



https://github.com/tgalatyuk/QCD_caloric_curve



TG., JPS Conf.Proc. 32 (2020) 010079

THE HADES COLLABORATION

38. HADES Collaboration Meeting, 2-6 March 2020